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Joint Research Centre

GEN ENERGIJA

Nuclear Science with High Intensity Lasers

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Institute for Transuranium Elements,
Karlsruhe, Germany

itu

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- **Introduction to Electron and Ion Acceleration by Lasers**
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  - Electron and ion acceleration principles
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  - Electrons, protons, neutrons, Bremsstrahlung, …
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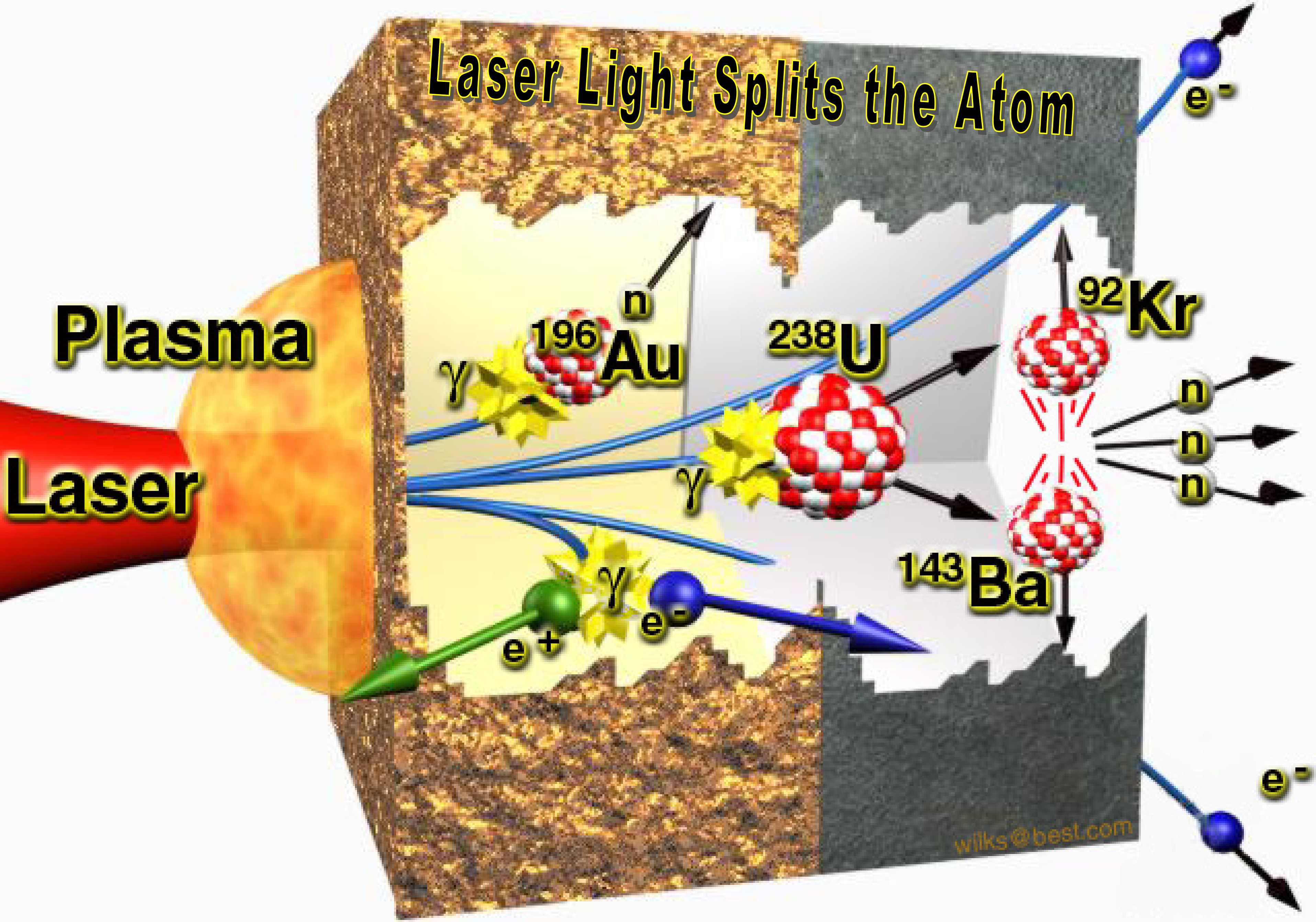

Laser Light Splits the Atom
Plasma
Laser
n
196Au
γ
238U
γ
92Kr
n
n
n
143Ba
γ
e-
e+
e-
e-
wilks@best.com

Theoretical Indication (1988)

- **Boyer et al. in 1988 in *Phys. Rev. Let.* proposed the possibility of inducing nuclear transitions using a laser**

VOLUME 60, NUMBER 7 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1988

Possibility of Optically Induced Nuclear Fission

K. Boyer, T. S. Luk, and C. K. Rhodes
Laboratory for Atomic, Molecular, and Radiation Physics, Department of Physics, University of Illinois at Chicago, Chicago, Illinois 60680
(Received 15 June 1987)

The process of nuclear fission induced by nonlinear radiative coupling to atomic electrons is considered. For 248-nm radiation at an intensity of $\simeq 10^{21}$ W/cm^2, highly relativistic currents are produced which can couple to the fission mode of nuclear decay. With irradiation for a time of $\simeq 100$ fs, the results indicate a fission probability of $\simeq 10^{-5}$ for $^{238}_{92}$U nuclei located at the surface of a solid target, a value several orders of magnitude above the limit of detection.

- **They even calculated expected reaction rates for inducing (γ,f) reactions in ^{238}U nuclei located on a surface of a solid target**

Experimental Demonstration

- **The first successful nuclear reaction experiment on a laser was performed at VULCAN, RAL (UK) in 2000, shortly followed by NOVA, LLNL (USA).**

VOLUME 84, NUMBER 5 PHYSICAL REVIEW LETTERS 31 JANUARY 2000

Photonuclear Physics when a Multiterawatt Laser Pulse Interacts with Solid Targets

ark,[2] I. Watts,[2] F. N. Beg,[2]
D. Neely,[3] R. J. Clark,[3]
l J. Magill[6]

Photonuclear physics

Laser light splits atom

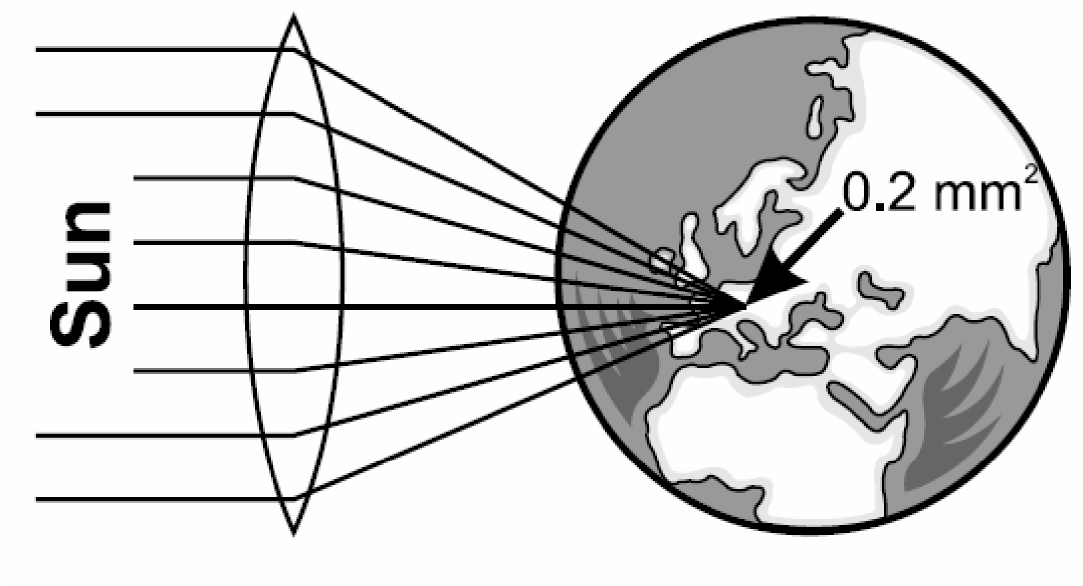
Donald Umstadter

NATURE | VOL 404 | 16 MARCH 2000 | www.nature.com

- **This demonstrated the ability to initiate nuclear reactions without recourse to large scale reactors, particles accelerators or other traditional radiation sources.**

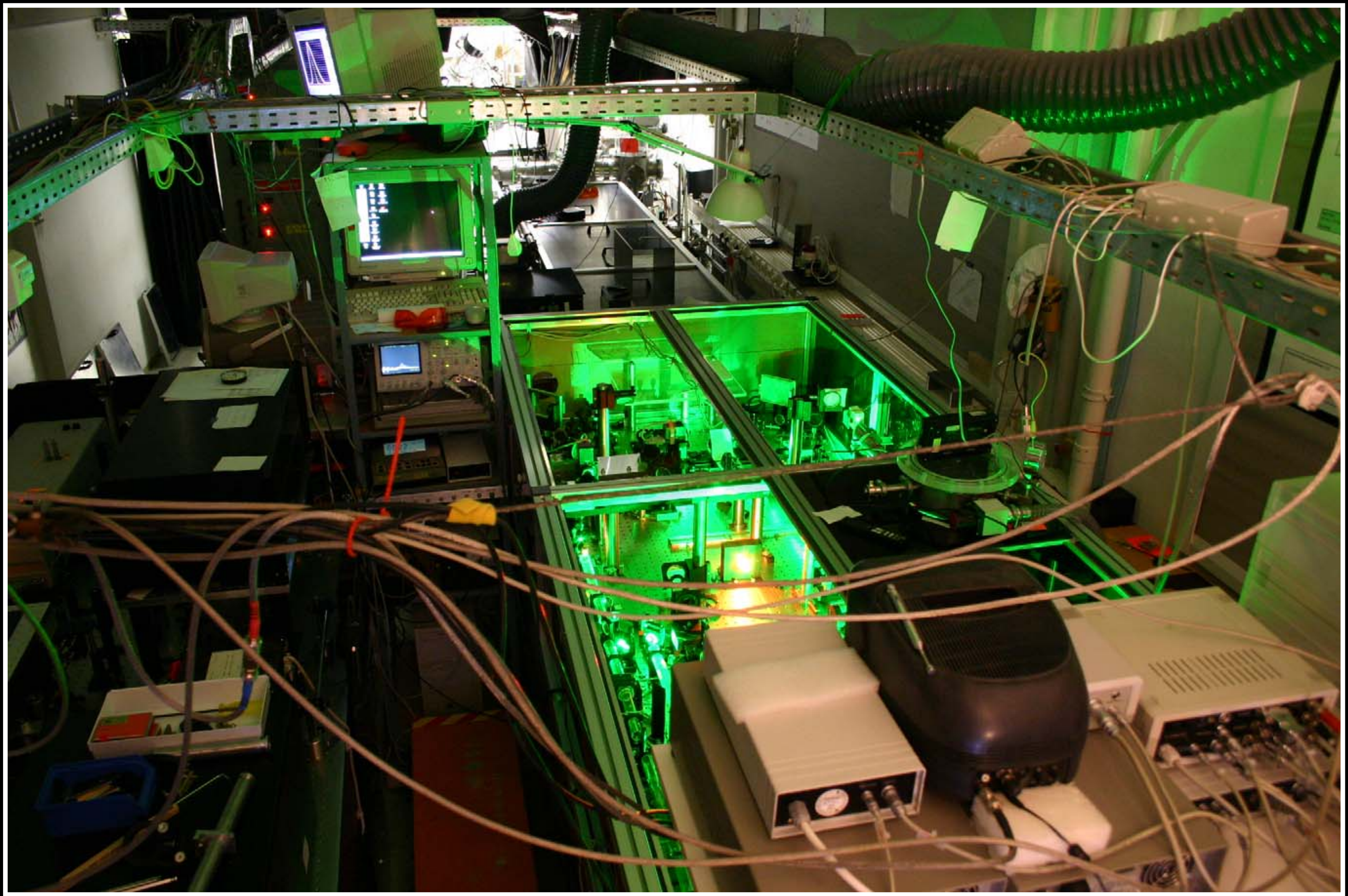
Extremely High Focal Intensity

- Light intensities of the order of **10^{20}W/cm^2** in the focal spot of a laser have become achievable in the last fey years.
- This intensity is equivalent to **all sun light incident on earth** focused onto a spot of **0.2mm^2**.



- I >10^{18} W/cm^2 leads to plasma with electrons having relativistic speeds.
- I $\approx 10^{20}$ W/cm^2 creates a plasma with temperatures $\approx 10^{10}$ K.

Terawatt Lasers: Target Irradiance >10^{18} W/cm^2



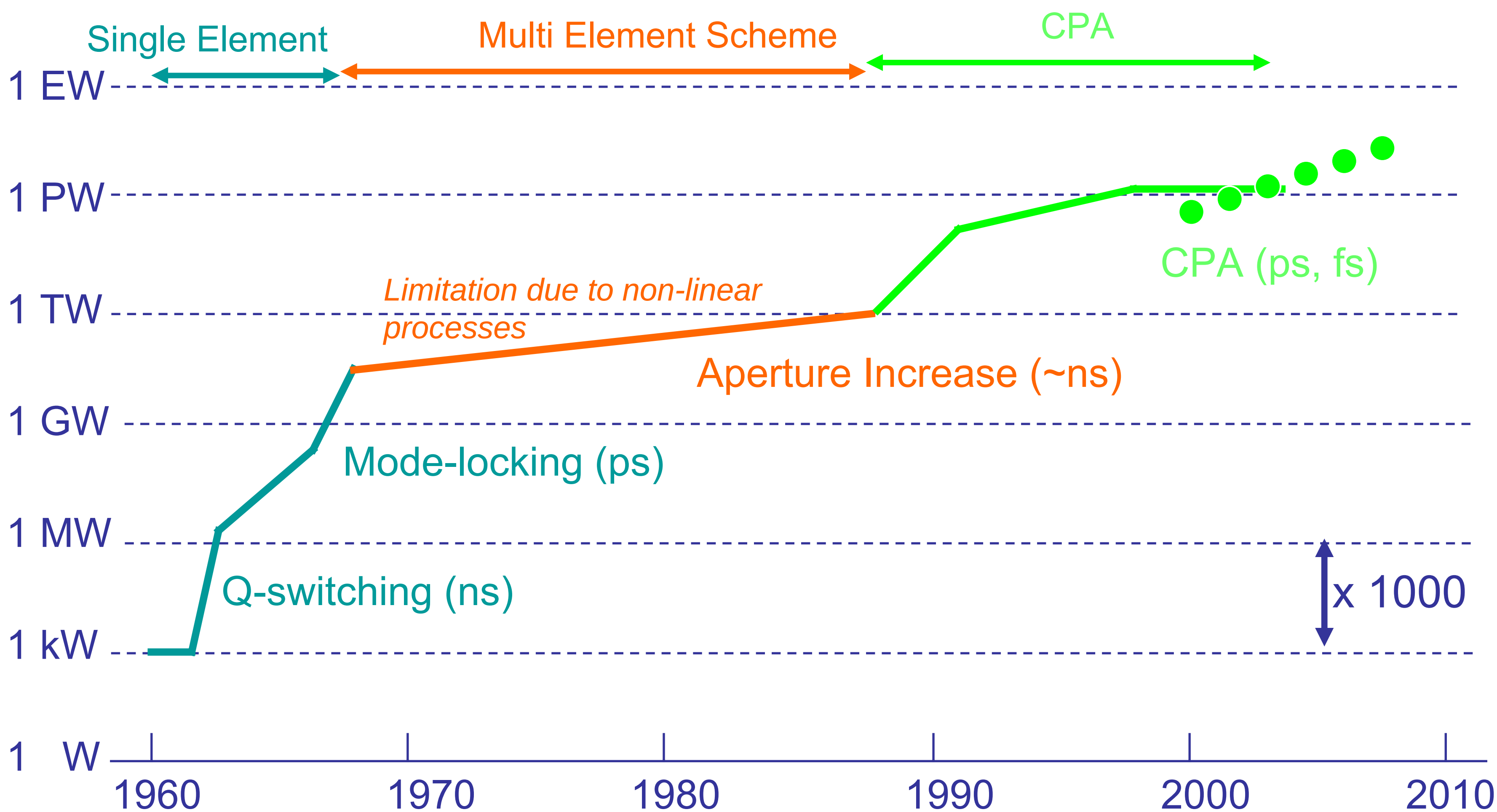
JETI laser at Jena University

TW Lasers

How to reach target irradiance in excess of 10^{18} W/cm^2 ?

- **1 TW = 10^{12} W**
- **How to get 10 TW, 100 TW or more? (1 PW = 10^{15} W)**
  Total energy consumption of the world in year 2000 was 450 EJ.
  "Average" manmade power generation on our planet is 450×10^{18} J / 3.156×10^{7} s = **14 TW**.
  Power of the Saturn V rocket at lift-off was **0.1 TW**.
- **Short laser pulse!**
  – large kJ lasers typically have 100 J in 1 ps
    - 100 J / 1 ps = 100 J / 10^{-12} s = 100 TW
  – table-top lasers have around 1 J in 100 fs
    - 1 J / 100 fs = 1 J / 100×10^{-15} s = 10 TW
- **Small focal spot!**
  – focus to spots of few 10 µm^2 (1 µm^2 = 10^{-8} cm^2)
    - 10 TW / 10 µm^2 = 10^{19} W/cm^2

History of Laser Development



Chirped-pulse Amplification

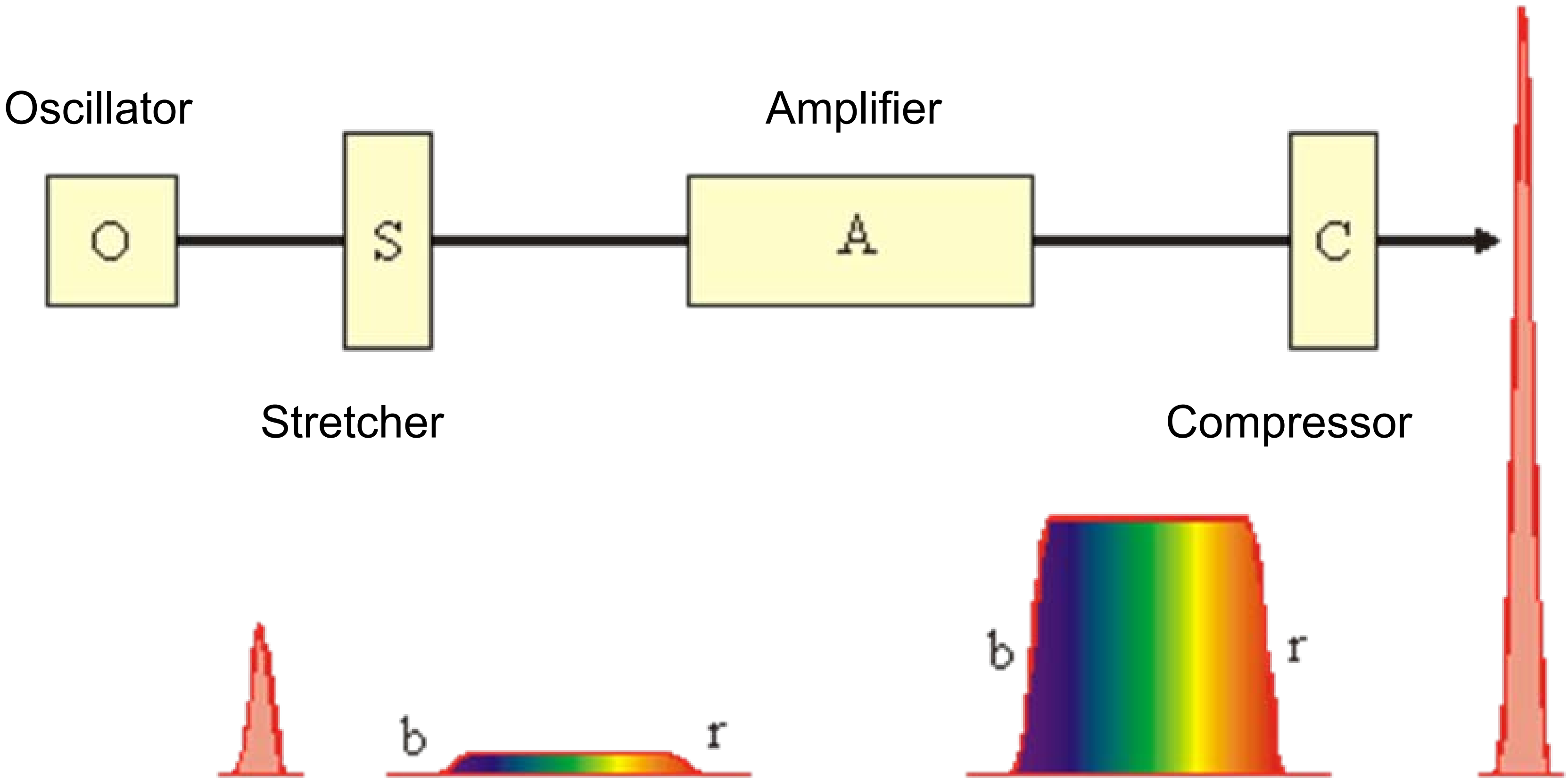


Diagram showing the principle of chirped-pulse amplification (CPA). The oscillator output (O) is stretched using the diffraction gratings (S) such that the red frequency components (r) travel ahead of the blue (b). The peak intensity is reduced in the process. The stretched pulse is then amplified in a regenerative or multipass amplifier (A) before recompression in a grating-pair compressor (C).

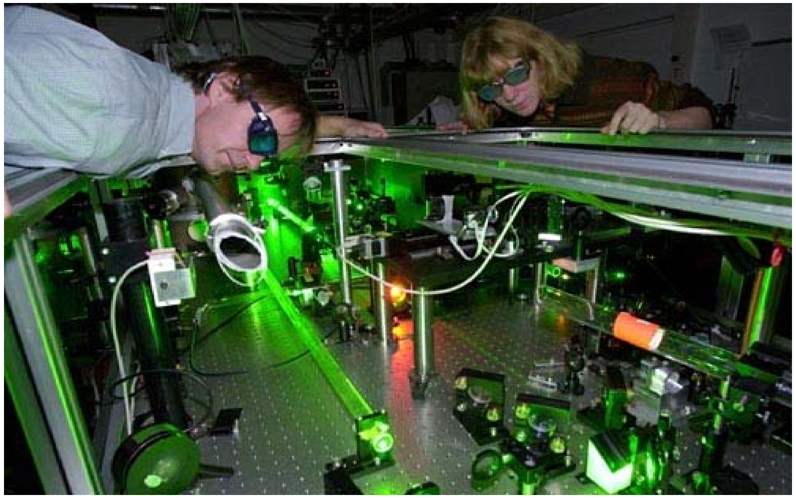
Large lasers installations – kilo Joule lasers

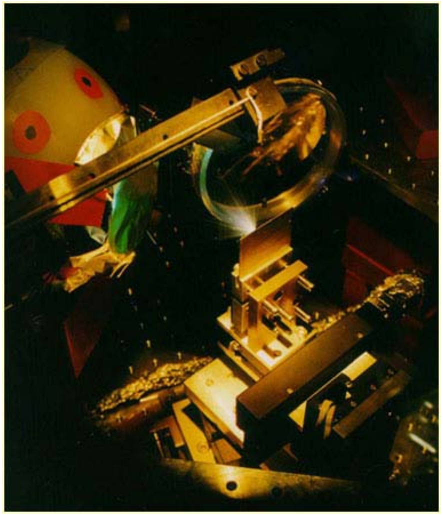
- **The VULCAN laser**
- **Multi beam glass laser system operating at almost** 1000 TW
- **Can deliver pulses with energy on target up to** 500 J **with pulse length about** 0.5 ps
- **Due to big energy in one pulse the beam diameter must be large enough. For example, diameter is approaching 70cm**
- **Repetition rate: one shot every 30 minutes**
- **Focused laser light intensity on target up to** 10^{21} W/cm^2

Terawatt table-top lasers: T^3 lasers

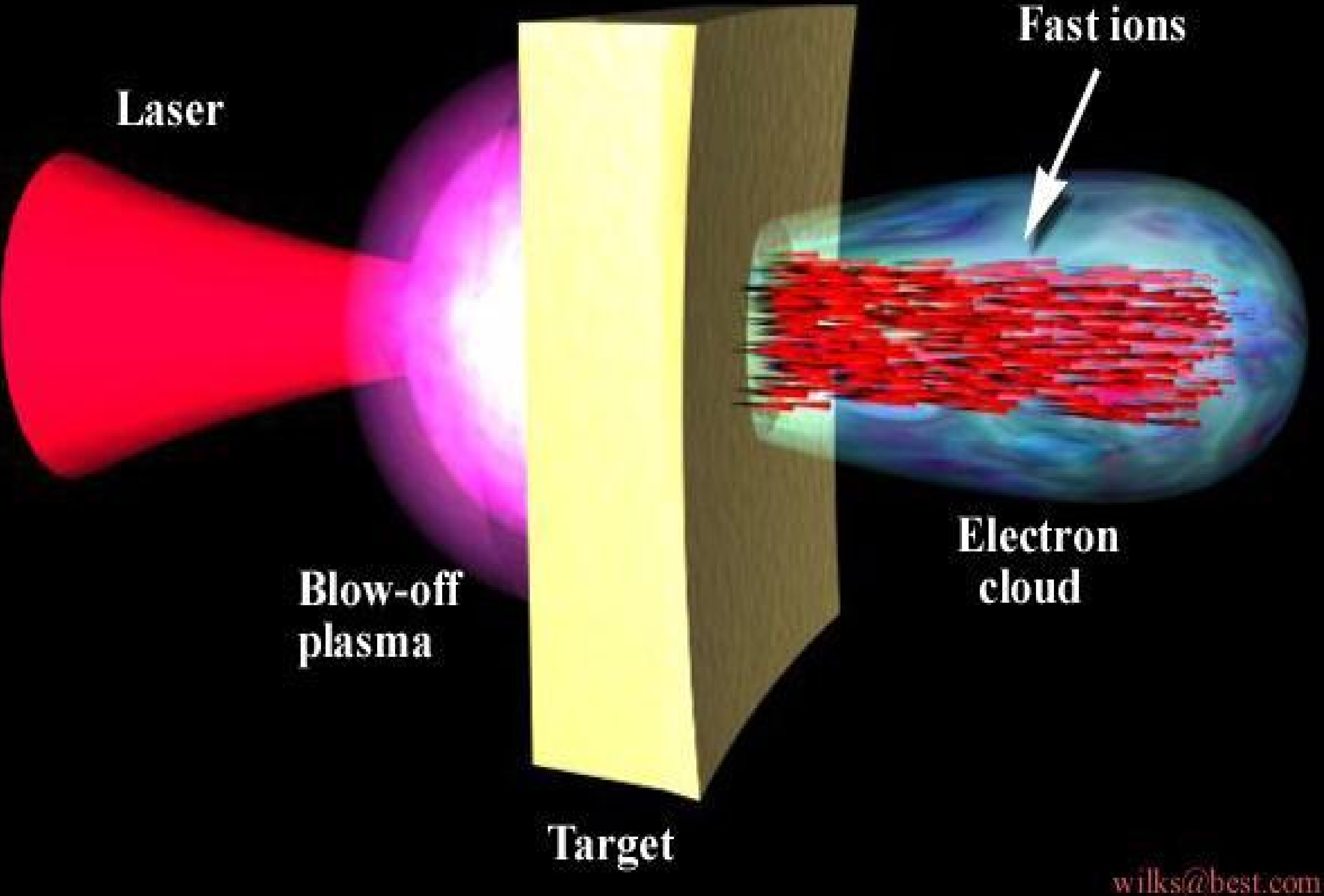
- Jena Terawatt laser (JETI)
- Single beam table-top laser system operating at 10 TW
- Delivers pulses with energy on target up to 1 J with pulse length 80 fs
- Repetition rate: 10 Hz
- Focused laser light intensity on target up to 2×10^{19} W/cm^2

- Diode pumped table-top lasers under construction will deliver more than 100 J in less than 100 fs (100 TW and more) (POLARIS)





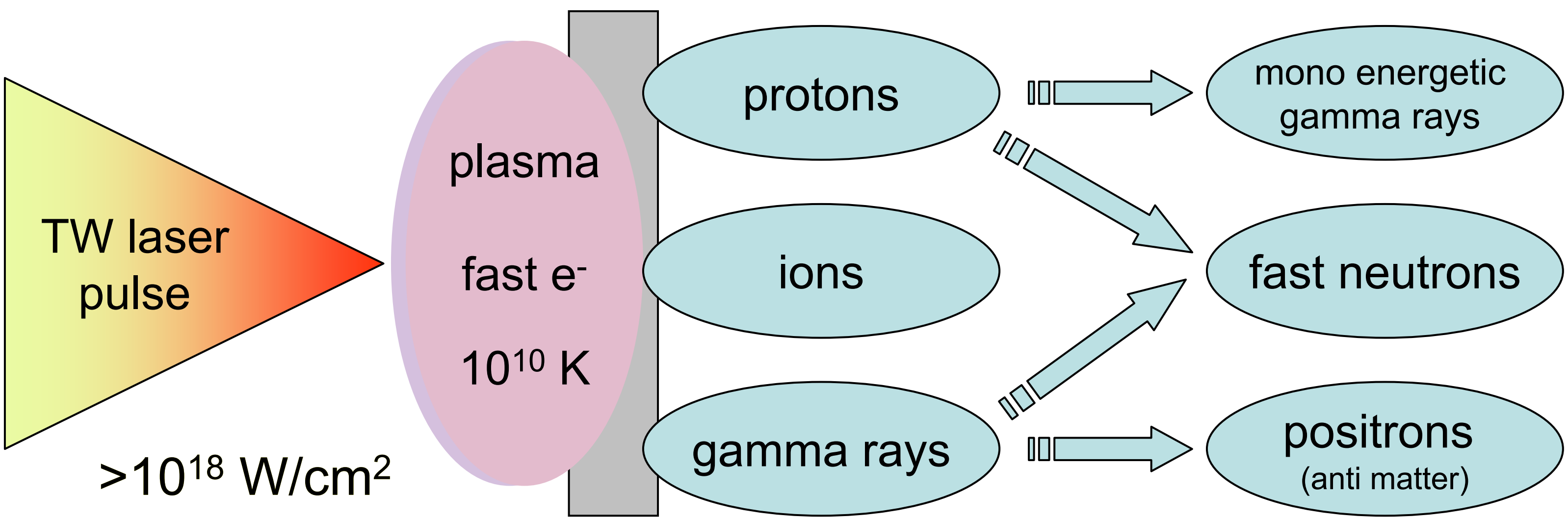
Electron and Ion Acceleration



Energy Transfer – The Overview

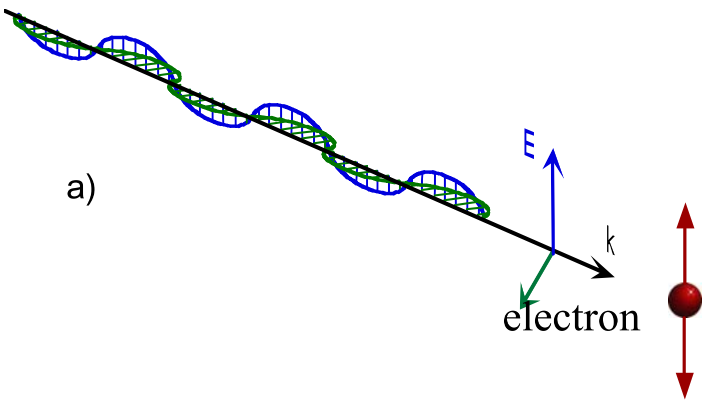
The cascade process of energy transfer from the laser pulse to the radiation

- **Primary processes are due to the action of the laser EM field on a plasma**
- **Fast electrons initiate secondary processes**



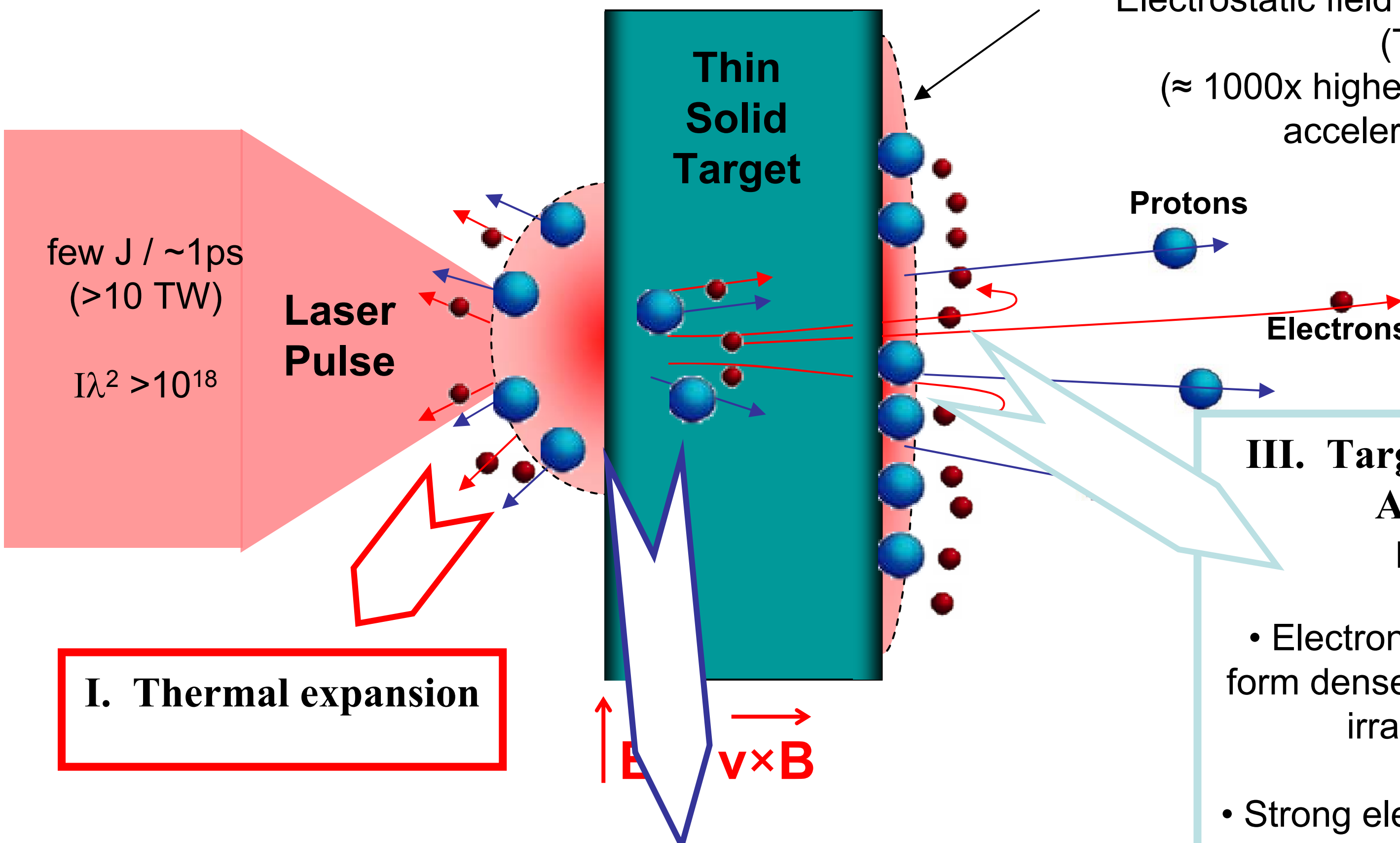
Electron acceleration (relativistic effects)

classical optics



Proton acceleration

Electrostatic field in the order of MV/μm (TV/m)
(≈ 1000x higher than conventional acceleration fields)



II. Front-surface charge separation

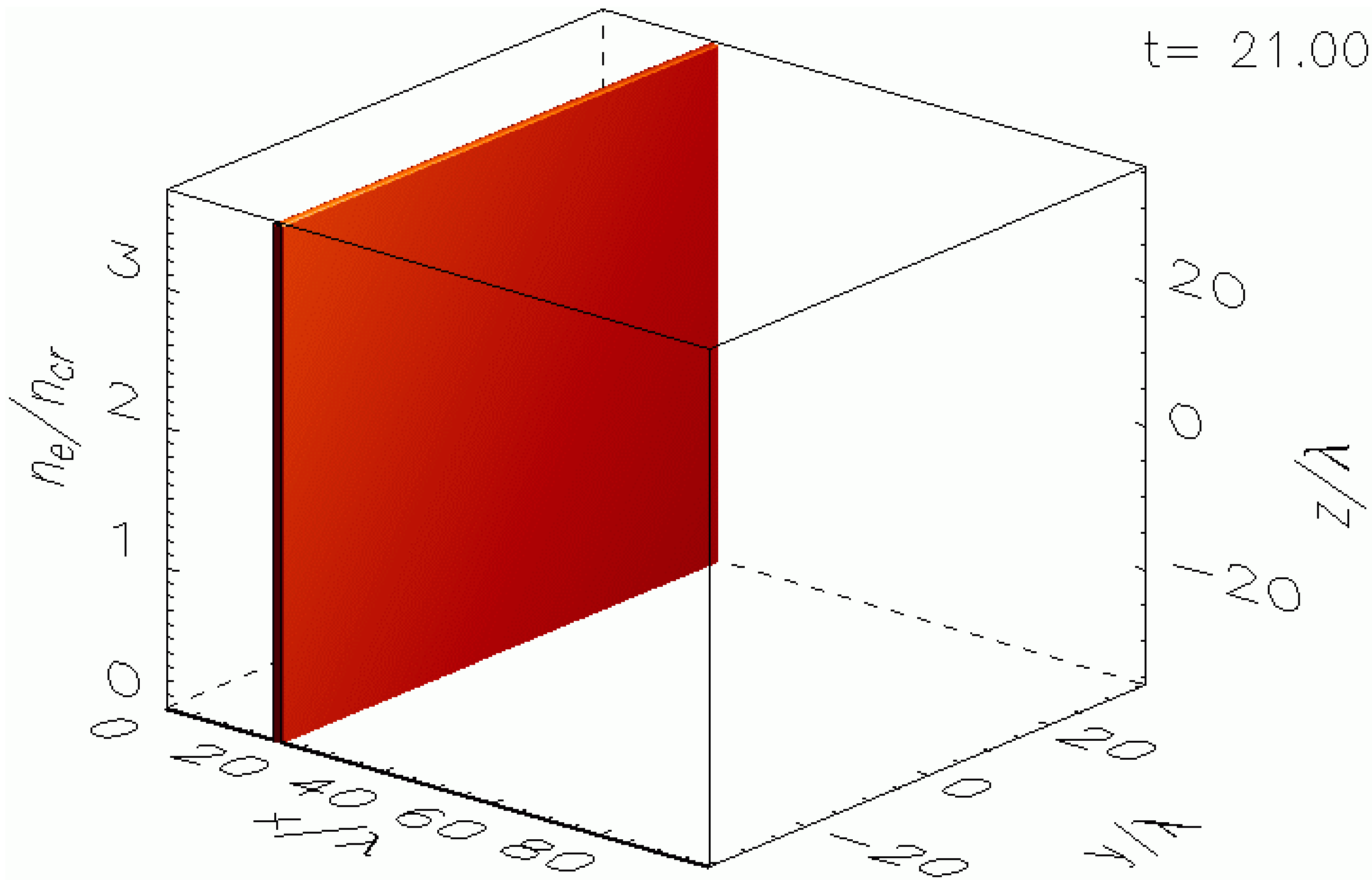
Static limit: $T_i \sim T_e$

III. Target Normal Sheath Acceleration

$E_i \sim 10 \times T_e$

- Electrons penetrate target & form dense sheath on rear, non-irradiated surface
- Strong electrostatic sheath field ionizes surface layer ($E_o \sim kT / e\lambda_d \sim$ MV/μm)
- Rapid (~ps) acceleration in expanding sheath produces very laminar ion beam

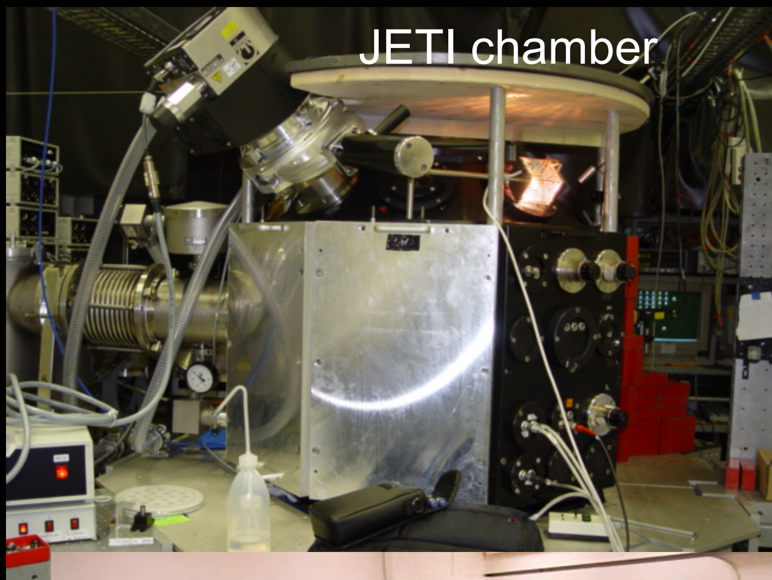
Proton acceleration simulation

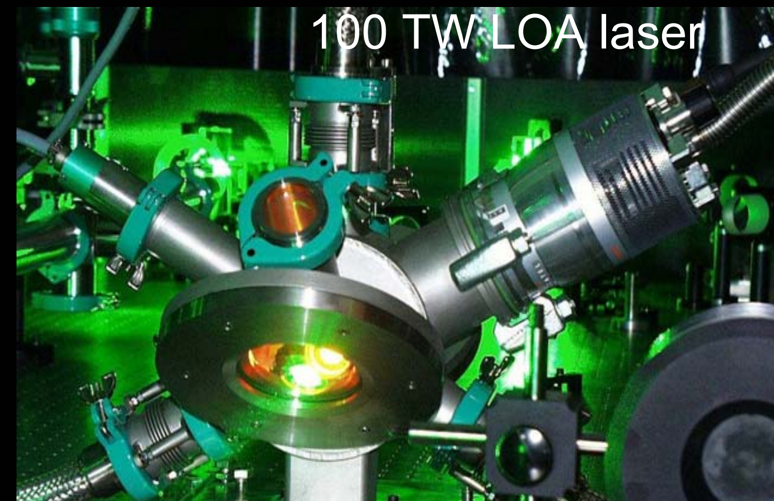


Ion (p+) density animation. Laser pulse goes from left to right.
The black curve shows the ion density along the laser pulse (10^{23} W/cm^2) axis.

T. Esirkepov et al., PRL **92**, 17 (175003) 2004

Nuclear Reactions Triggered by Lasers

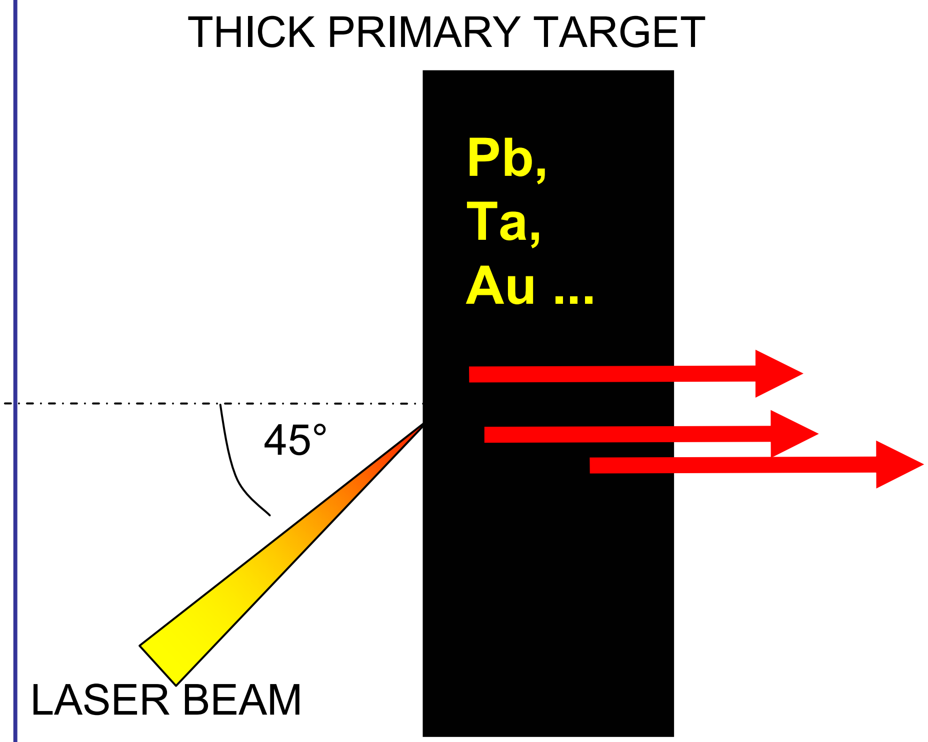


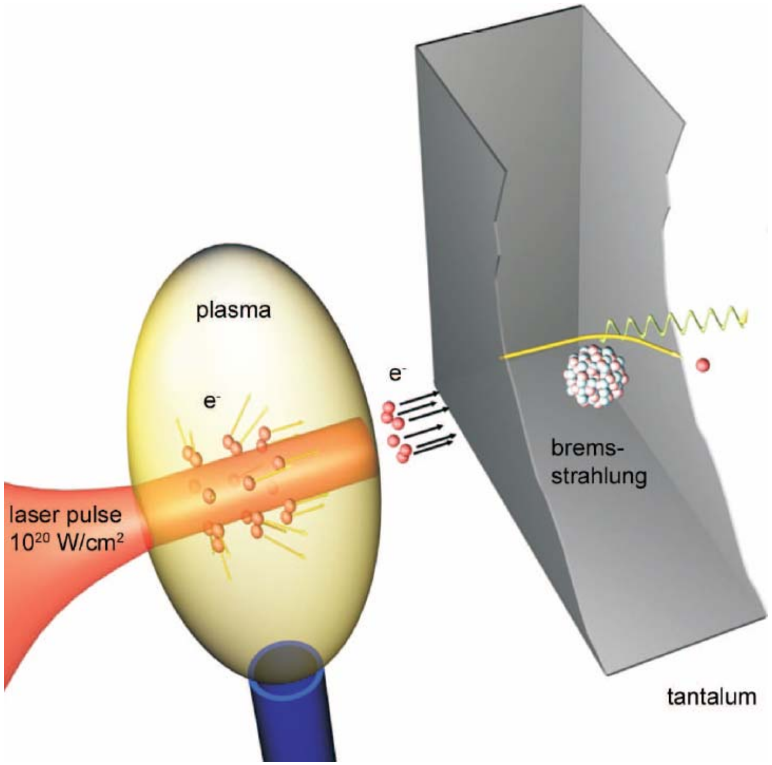


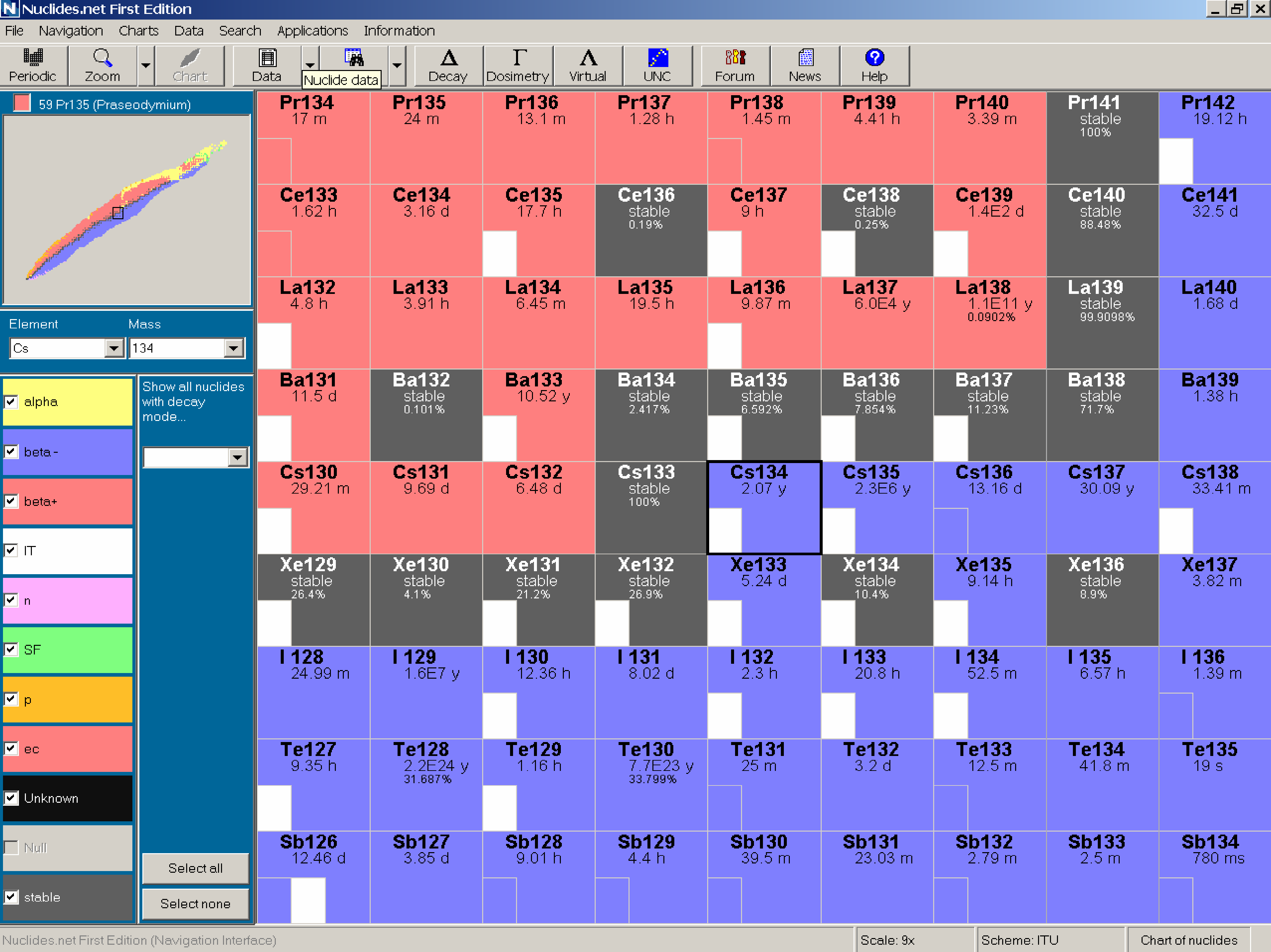
UHI10 target chamber at SLIC

Bremsstrahlung induced reactions

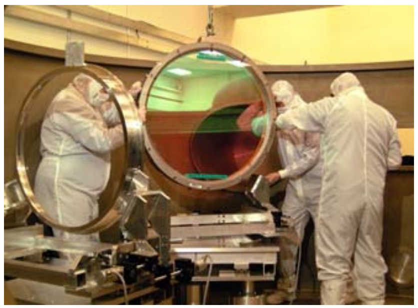
- **Multi-MeV electrons are stopped in thick high Z material**
- **They radiate typical bremsstrahlung γ rays (few 10 MeV)**






Nuclides.net First Edition
File Navigation Charts Data Search Applications Information
Periodic Zoom Chart Data Nuclide data Decay Dosimetry Virtual UNC Forum News Help
59 Pr135 (Praseodymium)
Element Mass
Cs 134
alpha
beta-
beta+
IT
n
SF
p
ec
Unknown
Null
stable
Show all nuclides with decay mode...
Select all
Select none
Pr134 17 m
Pr135 24 m
Pr136 13.1 m
Pr137 1.28 h
Pr138 1.45 m
Pr139 4.41 h
Pr140 3.39 m
Pr141 stable 100%
Pr142 19.12 h
Ce133 1.62 h
Ce134 3.16 d
Ce135 17.7 h
Ce136 stable 0.19%
Ce137 9 h
Ce138 stable 0.25%
Ce139 1.4E2 d
Ce140 stable 88.48%
Ce141 32.5 d
La132 4.8 h
La133 3.91 h
La134 6.45 m
La135 19.5 h
La136 9.87 m
La137 6.0E4 y
La138 1.1E11 y 0.0902%
La139 stable 99.9098%
La140 1.68 d
Ba131 11.5 d
Ba132 stable 0.101%
Ba133 10.52 y
Ba134 stable 2.417%
Ba135 stable 6.592%
Ba136 stable 7.854%
Ba137 stable 11.23%
Ba138 stable 71.7%
Ba139 1.38 h
Cs130 29.21 m
Cs131 9.69 d
Cs132 6.48 d
Cs133 stable 100%
Cs134 2.07 y
Cs135 2.3E6 y
Cs136 13.16 d
Cs137 30.09 y
Cs138 33.41 m
Xe129 stable 26.4%
Xe130 stable 4.1%
Xe131 stable 21.2%
Xe132 stable 26.9%
Xe133 5.24 d
Xe134 stable 10.4%
Xe135 9.14 h
Xe136 stable 8.9%
Xe137 3.82 m
I 128 24.99 m
I 129 1.6E7 y
I 130 12.36 h
I 131 8.02 d
I 132 2.3 h
I 133 20.8 h
I 134 52.5 m
I 135 6.57 h
I 136 1.39 m
Te127 9.35 h
Te128 2.2E24 y 31.687%
Te129 1.16 h
Te130 7.7E23 y 33.799%
Te131 25 m
Te132 3.2 d
Te133 12.5 m
Te134 41.8 m
Te135 19 s
Sb126 12.46 d
Sb127 3.85 d
Sb128 9.01 h
Sb129 4.4 h
Sb130 39.5 m
Sb131 23.03 m
Sb132 2.79 m
Sb133 2.5 m
Sb134 780 ms
Nuclides.net First Edition (Navigation Interface)
Scale: 9x
Scheme: ITU
Chart of nuclides

Results: ^{129}I transmutation using (γ,n)



INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS D: APPLIED PHYSICS
J. Phys. D: Appl. Phys. 36 (2003) L79–L82 PII: S0022-3727(03)67481-4

RAPID COMMUNICATION

Laser-driven photo-transmutation of ^{129}I—a long-lived nuclear waste product

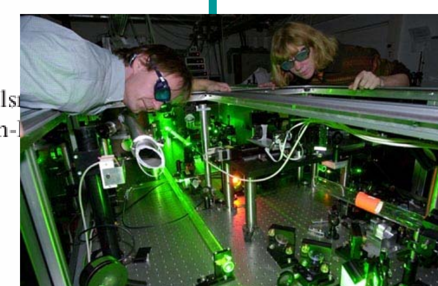
K W D Ledingham[1,6], J Magill[2], P McKenna[1], J Yang[1], J Galy[2], R Schenkel[2], J Rebizant[2], T McCanny[1], S Shimizu[1], L Robson[1], R P Singhal[3], M S Wei[4], S P D Mangles[4], P Nilson[4], K Krushelnick[4], R J Clarke[5] and P A Norreys[5]

Appl. Phys. B 00, 1–4 (2003)
DOI: 10.1007/s00340-003-1306-4
Applied Physics B
Lasers and Optics

Laser transmutation of iodine-129

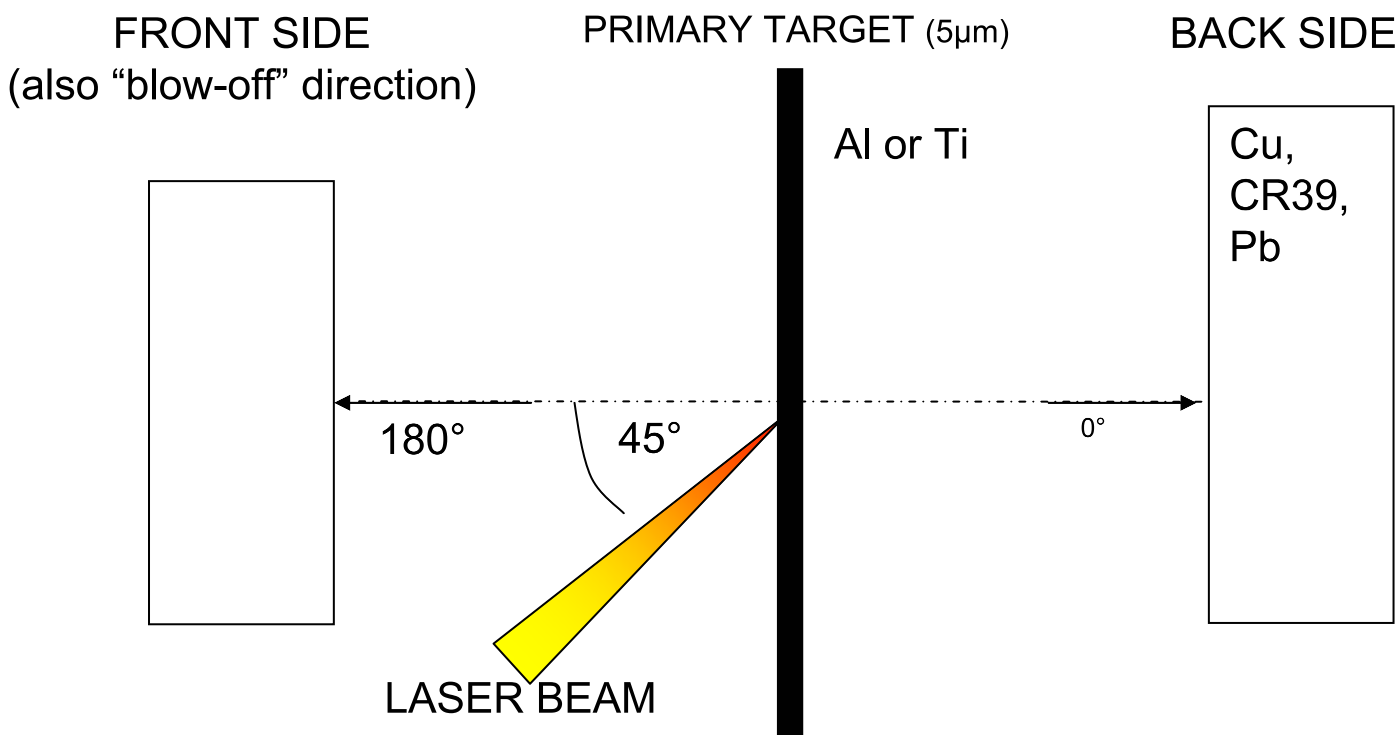
J. MAGILL[1,*]
H. SCHWOERER[2,*,✉]
F. EWALD[2]
J. GALY[1]
R. SCHENKEL[1]
R. SAUERBREY[2]

[1] European Commission, Institute for Transuranium Elements, Postfach 2340, 76125 Karls
[2] Institut für Optik und Quantenelektronik, Friedrich-Schiller-Universität Jena, Max-Wien-
07743 Jena, Germany



$$^{129}\text{I}\ \sigma_{(\gamma,n)} = 97 \pm 40\text{mb}$$

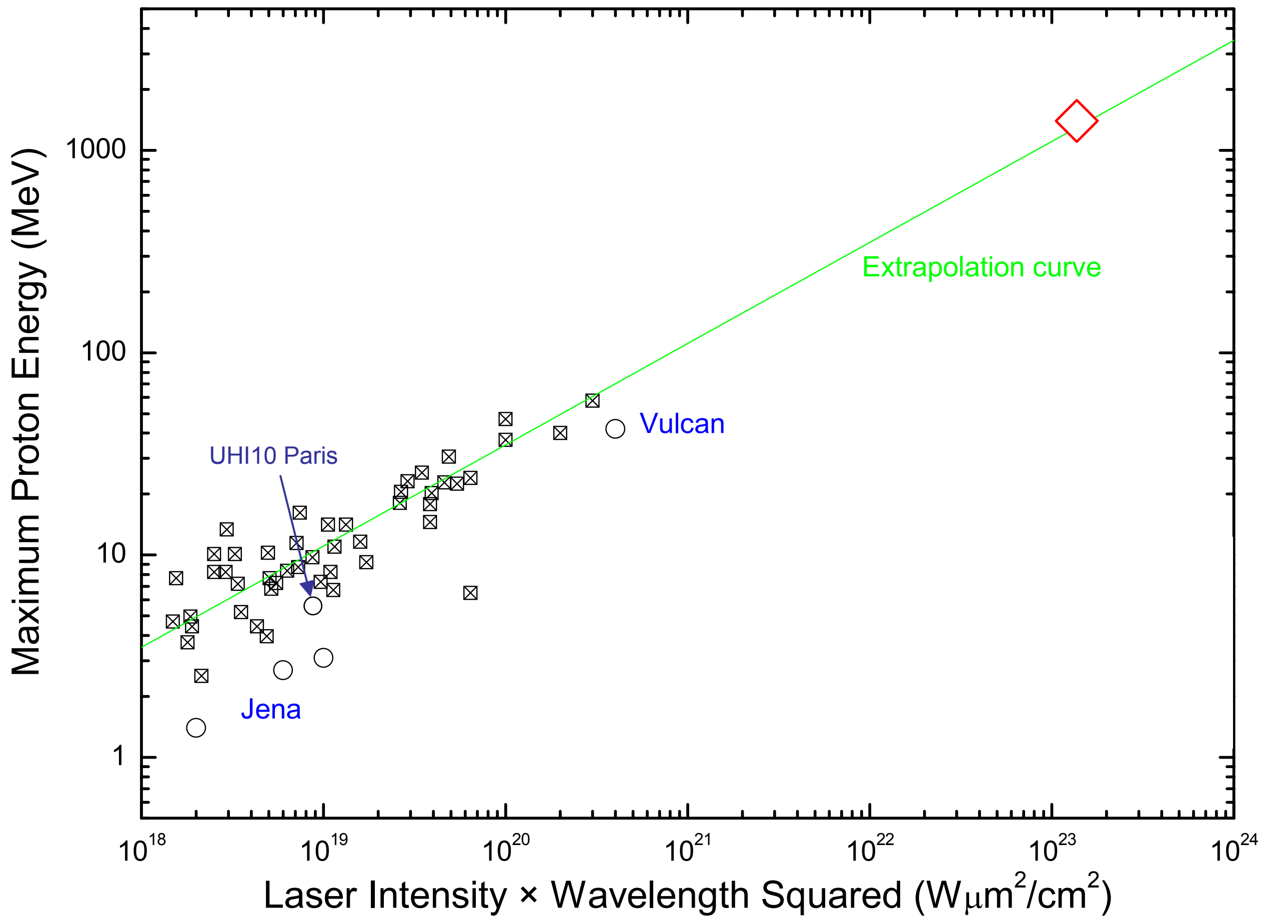
Proton induced reactions



Higher efficiency: 10 % to 20% achievable (even 50 %)

High-intensity, ultra-fast laser pulse: 10^{20} W/cm², λ ≈ 1 μm

Currently achievable proton energies



Maximum p^+ energy is a function of $I\lambda^2$

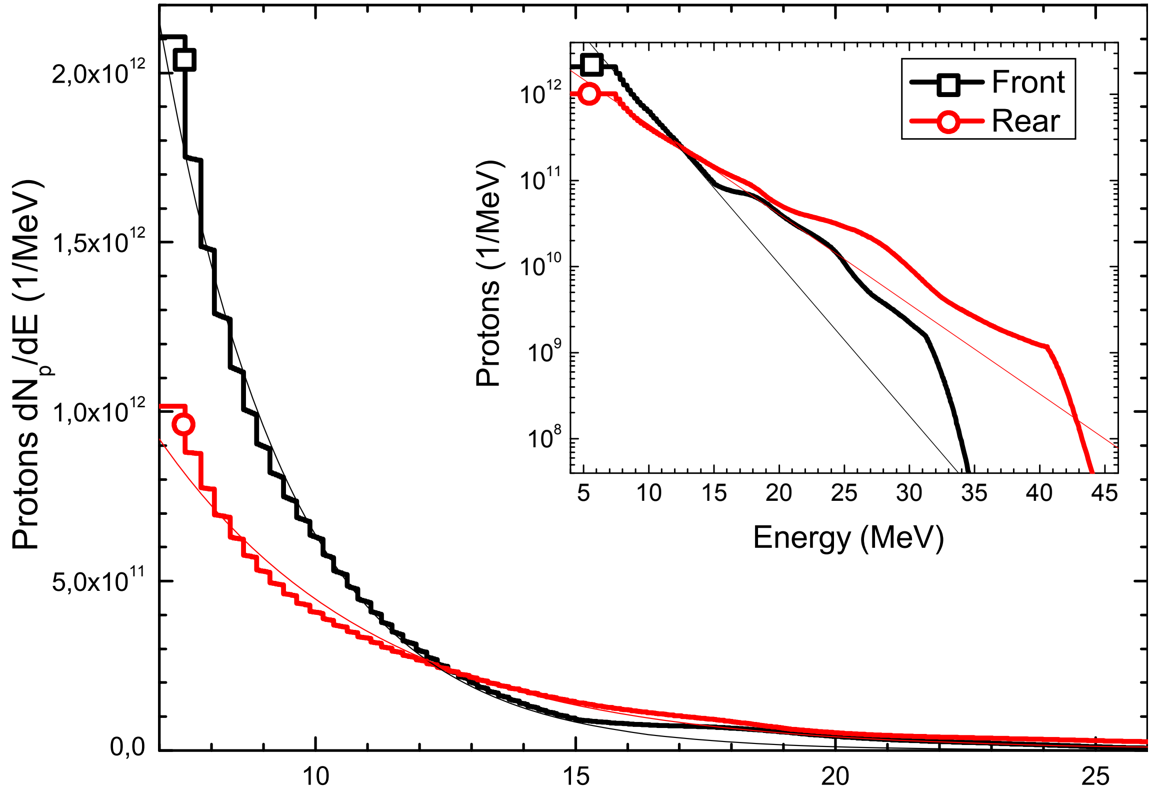
$$E_{max} = a(I\lambda^2)^{\alpha}$$

For $I\lambda^2 > 10^{19}$:
a ~ 4 or 3 x 10^{-9} MeV
$\alpha = 0.5$

Mendonca, Spencer, 2000

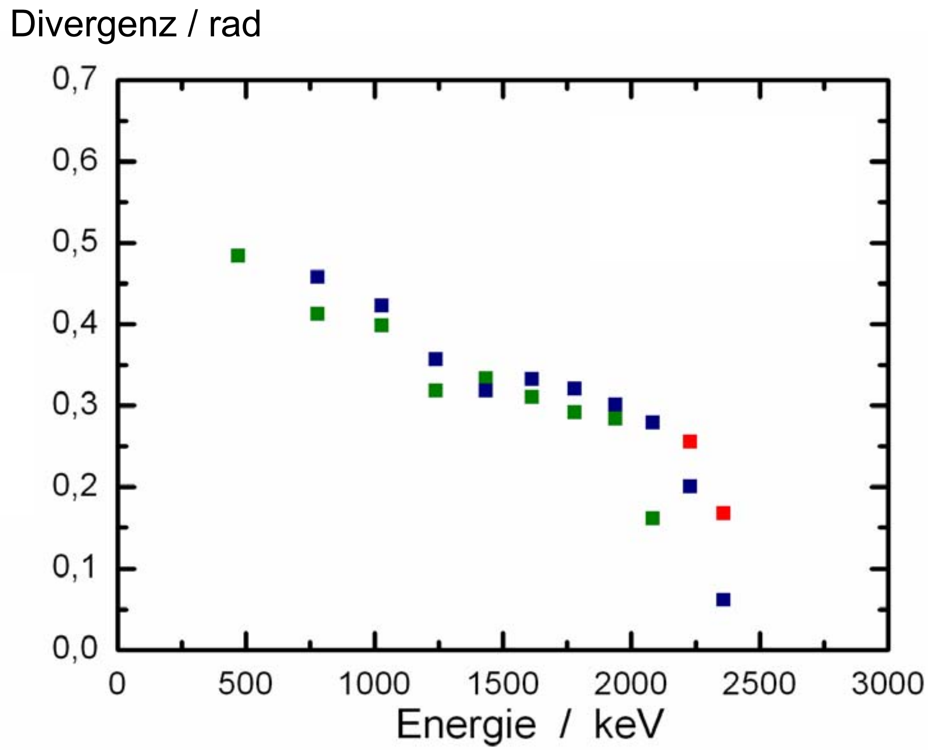
Maximum energies are presented. Average proton energy in the accelerated spectrum (Boltzman like spectrum) is approximately 5 to 10 times smaller.

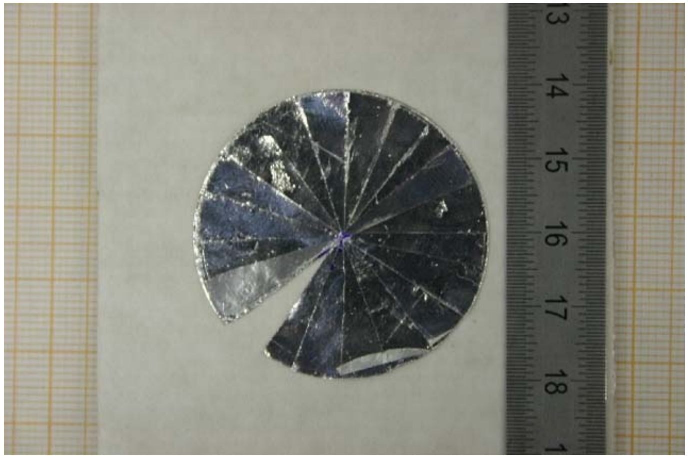
Example of Measured Proton Spectra



Temperature of the protons on the front side was 2.5 MeV and the temperature on the back side was 4.2 MeV. The total number of accelerated protons to energies above 10 MeV was 7×10^{11} for the front side and 5×10^{11} for the back side.

Example of Measured Proton Beam Divergence (Jena / ITU / IJS)



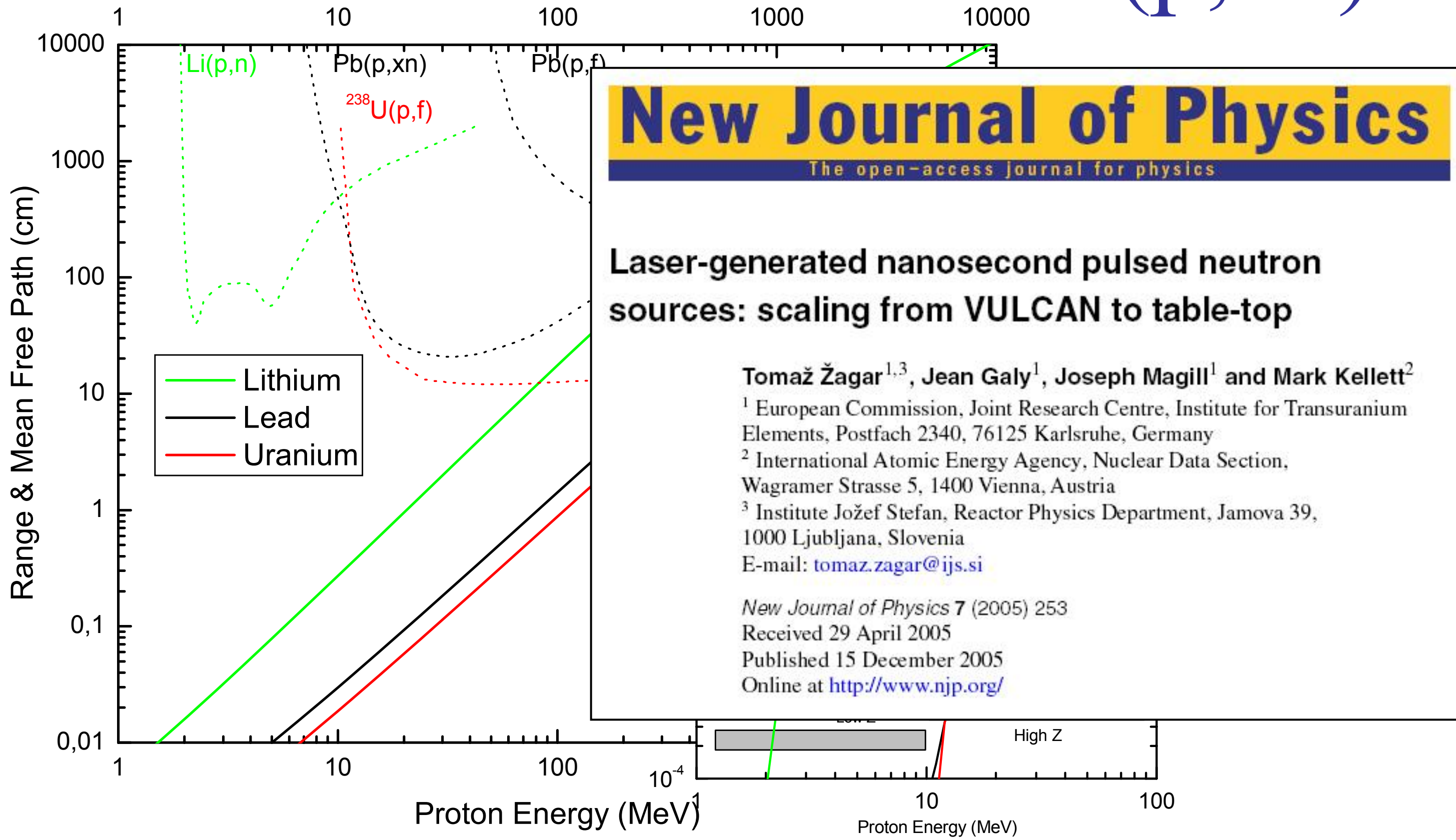


Aluminium filter (IJS)

Neutron driven nuclear reactions

- **Neutrons are "traditional tool" for nuclear reactions**
- **Neutral, long "range", no threshold for (n,γ)**
- **Numerous neutron applications already in use**
  - Radiograph
  - Geophysics
  - Medicine
  - Material science for fission & fusion technology
  - Nuclear physics research
  - Security!
- **New, pulsed, compact, neutron source!**

Proton to neutron conversion (p,xn)



New Journal of Physics
The open-access journal for physics

Laser-generated nanosecond pulsed neutron sources: scaling from VULCAN to table-top

Tomaž Žagar[1,3], **Jean Galy**[1], **Joseph Magill**[1] **and Mark Kellett**[2]

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[2] International Atomic Energy Agency, Nuclear Data Section, Wagramer Strasse 5, 1400 Vienna, Austria
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Received 29 April 2005
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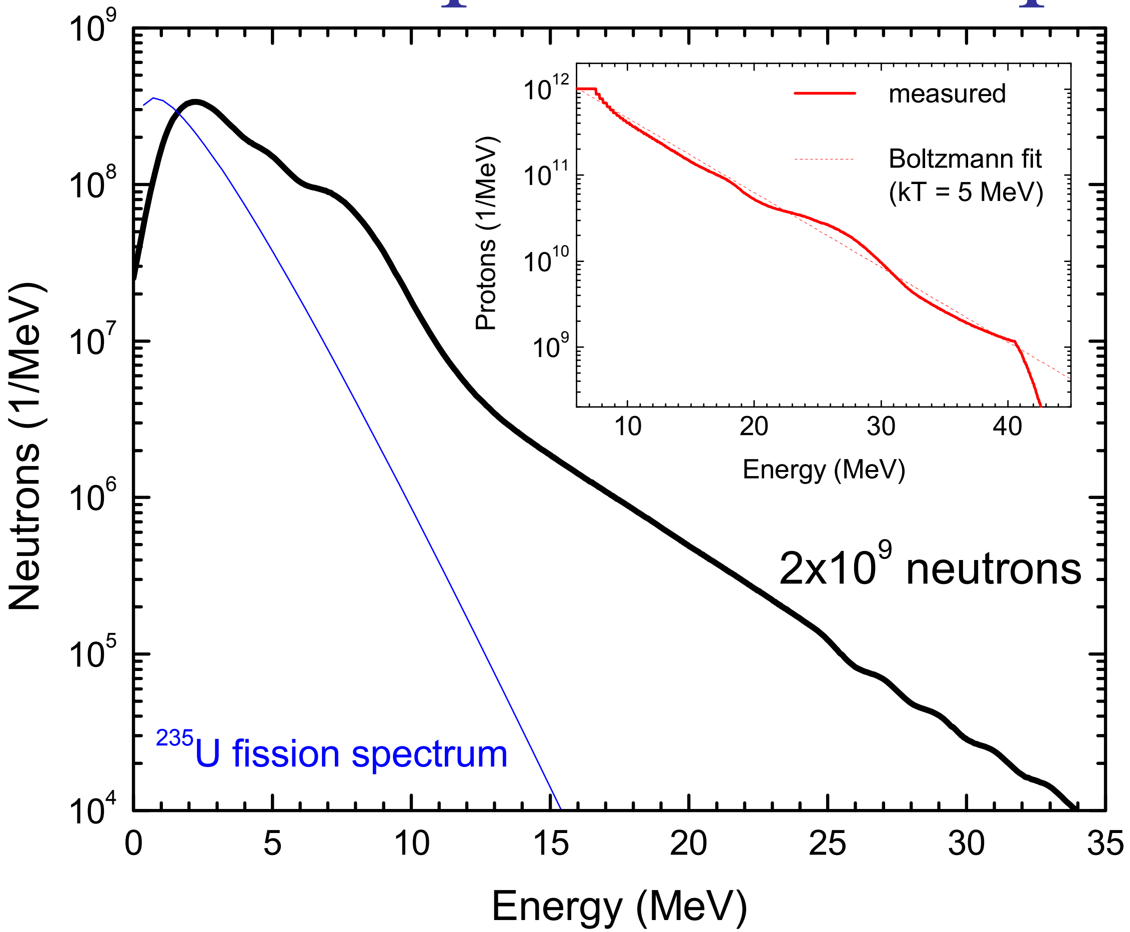
Online at http://www.njp.org/

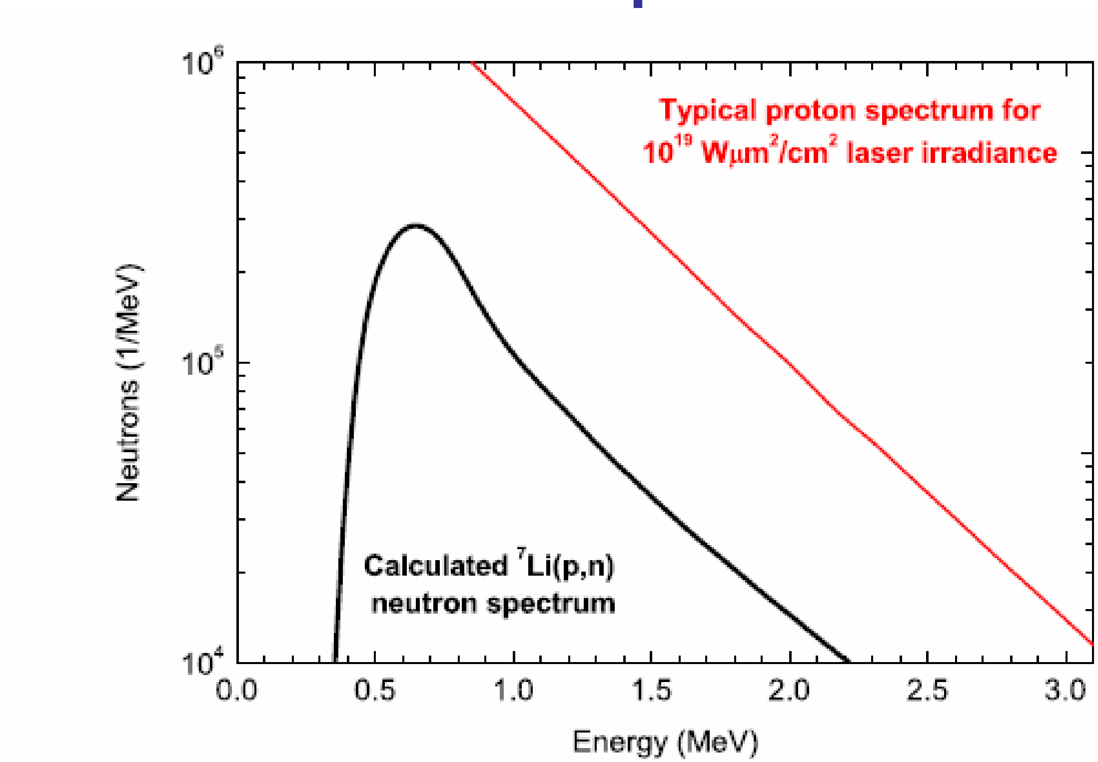
Proton ranges (solid lines) and mean free paths (dotted lines) for neutron generation reactions in the same materials as a function of incoming proton energy. Efficiency of proton to neutron conversion in different materials is shown in insert.

Neutron spectrum – ns pulse



The neutron spectra released in $^{nat}Pb(p,xn)Bi$ reactions in VULCAN experiment.

Neutron spectrum – ns pulse



Calculated neutron spectra released in ^{7}Li(p,n) reaction on table-top laser (UNI10).

Some research reactor sources	Flux for irradiation (neutrons $cm^{-2} s^{-1}$)	Strength (neutrons s^{-1})
250 kW TRIGA (General atomics)	2×10^{13}	7.8×10^{15}
62 MW ILL (Institut Laue-Langevin)	1.5×10^{15}	1.9×10^{18}
250 MW ATR (Idaho National Laboratory)	1.5×10^{15}	7.8×10^{18}
Some spallation sources	Average flux	Peak flux
	(neutrons $cm^{-2} s^{-1}$)	(neutrons $cm^{-2} s^{-1}$)
SINQ at Paul Scherrer Institute[a]	10^{14}	10^{14}
SNS at Oak Ridge (under const.)	10^{15}	10^{17}
Compact and portable neutron sources	Average strength (neutrons s^{-1})	
Radioactive neutron sources[b]	10^5–10^7	
Spontaneous fission sources[c]	Around 10^{10}	
Portable neutron generators[d]	10^8–10^{10}	

Experiment (reference)	Lancaster [19]	Yang [27]	Yang [27][a]	This paper
Reaction(s) used	$^7Li(p,n)^7Be$	$^{nat}Zn(p,xn)Ga$	$^7Li(p,n)^7Be$	$^{nat}Pb(p,xn)Bi$
Laser energy (J $shot^{-1}$)	69	230	230	400
Measured neutrons (neutrons $shot^{-1}$)	2×10^8	$\approx 10^{10}$	5×10^{10}	2×10^9
Average strength (neutrons s^{-1})	10^5	$\approx 10^7$	2×10^7	10^6
Peak strength (neutrons s^{-1})	2×10^{17}	$\approx 10^{19}$	5×10^{19}	2×10^{18}

Laser Generated Neutron Sources

Some General Properties

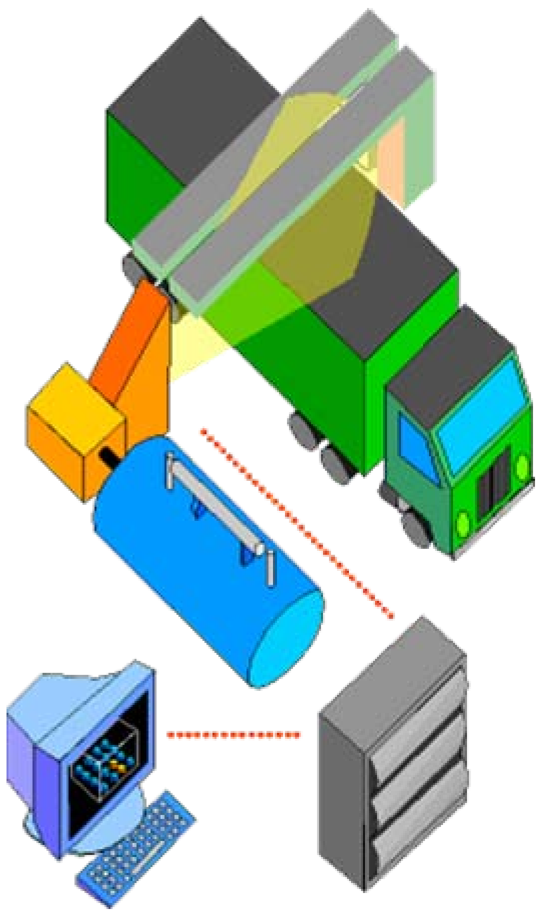
- Compact Table-Top Sources (!)
- Fast Neutrons – Broad Spectrum
- Forward Directed Beams
- Pulsed Operation
- Very Short Pulse Durations (!)
- High Repetition Rates
- Useful Source Strengths

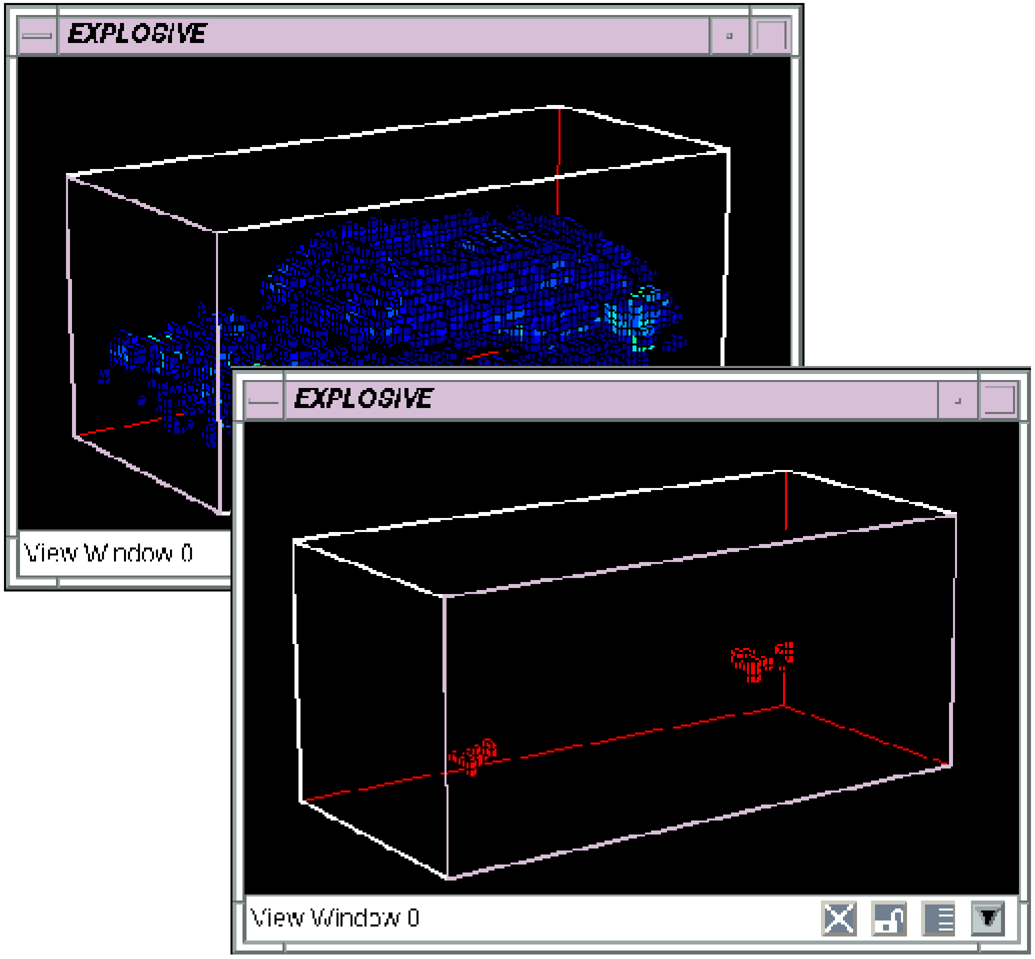
Applications for Pulsed Neutron Sources

Several fields of applications already in existence. One interesting example are security applications, for example detection of explosives and other illicit materials in so called "Homeland Security" field.

- PFNA - Pulsed Fast Neutron Analysis - measures the elemental contents (O, N, etc.) within small volume segments (exact 3D location) using time of flight principle
- For exact time of flight spectroscopy extremely short and well defined pulses of fast neutrons are required

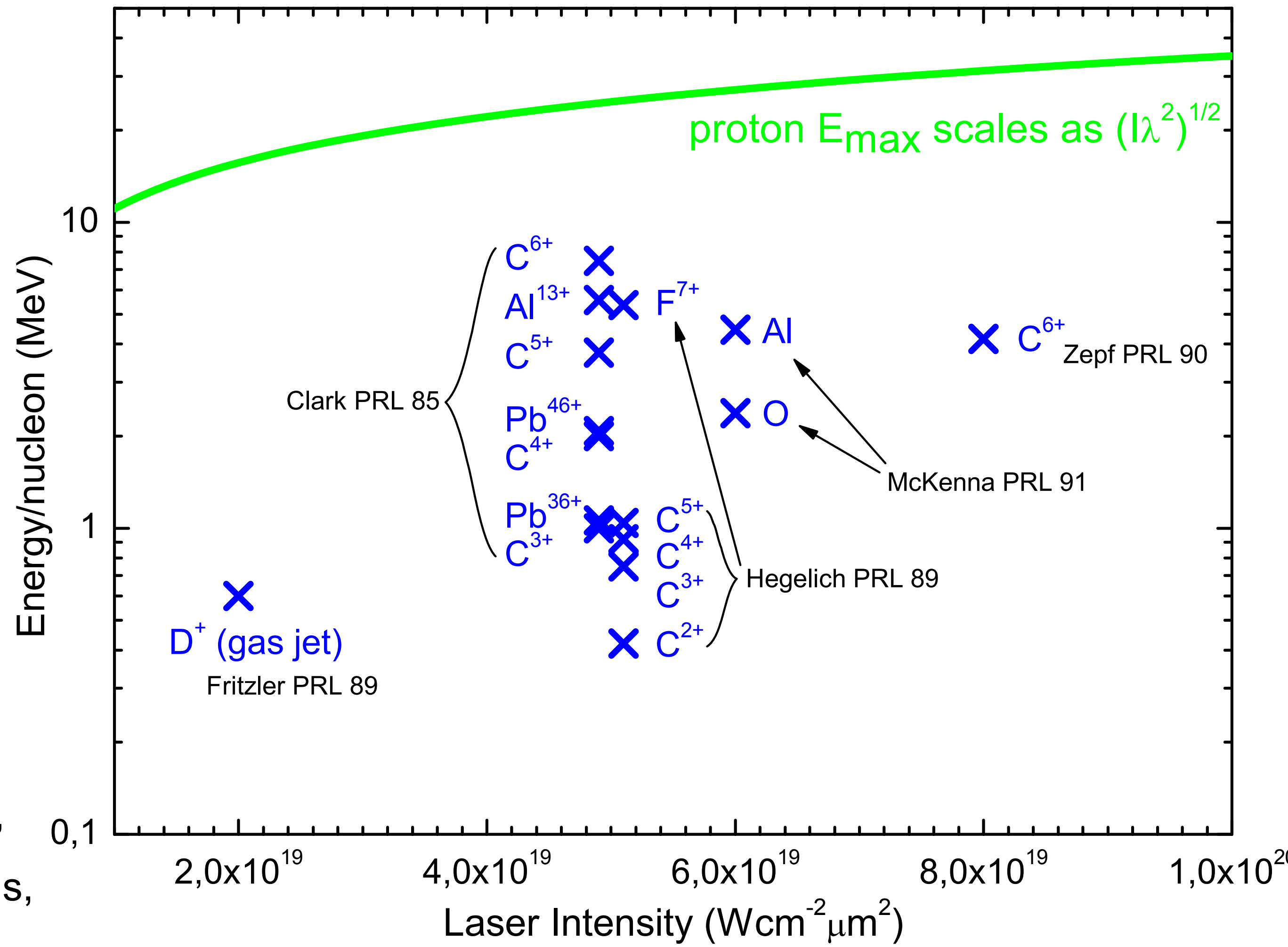
PFNA - Pulsed Fast Neutron Analysis





Ancore Corporation, Santa Clara, USA

Other Ions Accelerated by Lasers ?



40 MeV ^{16}O ions,

120 MeV ^{35}Cl ions,

500 MeV ^{208}Pb ions

Conclusion

- New way of inducing nuclear reactions
- This research field is developing fast with fast development of high intensity laser
- Currently laser light can directly accelerate electrons to relativistic speeds, and can consequently accelerate protons and other ions
- In near future lasers will be able to accelerate protons to relativistic speeds directly
- New table-top radiation sources will become available
- We have shown possible applications of laser accelerated electrons, protons, gammas, neutrons

THANK YOU FOR YOUR ATTENTION